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Infrastructure Retrofit Design via Composite Mechanics

CHRISTOS C. CHAMIS and PASCAL K. GOTSIS

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ABSTRACT

Select applications are described to illustrate the concept for retrofitting reinforced concrete infrastructure with fiber reinforced plastic laminates. The concept is first illustrated by using an axially loaded reinforced concrete column. A. reinforced concrete arch and a dome are then used to illustrate the versatility of the concept. Advanced methods such as finite element structural analysis and progressive structural fracture are then used to evaluate the retrofitting laminate adequacy. Results obtains show that retrofits can be designed to double and even triple the as-designed load of the select reinforced concrete infrastructures.

INTRODUCTION

Infrastructures are generally made from reinforced concrete. Concrete tends to crack, chip and damage as a result of inadvertent loads or overloads which may not have been accounted for in the initial design. The damage in infrastructure may extend to a state where the safety of that infrastructure becomes a major concern. Recently, a considerable effort is being expended on repairing damaged infrastructures by using fiber reinforced composites [1, 2 and 3]. This is natural since the repairing composites tend to be of thin laminates which are easily applicable to damaged infrastructures that are of cylindrical and flat surfaces in general. Different methods for designing and analyzing thin laminates have been developed and are available in many computer codes [4]. Recent research at Lewis Research Center demonstrated that damaged concrete structures and their repairing composites can be simulated simultaneously by laminate and composites mechanics analogies which are available in some of those computer codes [5]. The

Christos C. Chamis and Pascal K. Gotsis, of NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, OH 44135

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objective of the proposed paper is to describe the application of composite laminate in conjunction with progressive fracture concepts [6], to design retrofits for reinforced concrete structures such as columns, arches and domes. Another objective is to demonstrate that advanced technology developed for aerospace propulsion structures is readily transferable for infrastructure retrofitting. More fundamental aspects of simulating concrete from its constituents and subsequent application to model reinforced concrete structures are described [7]. Herein, the column is used to illustrate the concept while the arch and the dome are used to illustrate its versatility and its application to more complex structures. A schematic of the computational procedure use is shown in Figure 1.

RETROFIT CONCEPT ILLUSTRATION

Consider the concrete reinforced column shown in Figure 2. Assume that the column is made from concrete with 27.6 MPa (4 ksi) and steel with 276 MPa (40 ksi) yield strength. The column is designed for an ultimate load of (500k). The modulus of the concrete is 20.7 GPa (3 mpsi); that of the steel is 207 GPa (30 mpsi). The corresponding modulus of the column is 26.3 GPa (3.81 mpsi). The Poisson's ratio of the concrete column approximately 0.1. The column is designed for an ultimate load of 2223KN (500 kips). The corresponding stresses in the concrete are: 24.8 MPa (3600 psi) compression and 2.5 MPa (360 psi) tension. The compression stress in the steel is 248 MPa (36 ksi). All stresses are below their allowables with a safety margin of about 10 percent at ultimate load

If we now assume that the column could be overloaded by dynamic loads from earthquakes by a factor of 2, the compressive stresses in the concrete is 49.6 MPa (7200 psi) which exceed concrete compressive strength by about a factor of 2. The transverse tensile strength will also be exceeded by about the same factor. In the first case the concrete will crumble to loose gravel and in the second case, considerable spallation will occur. In either case the column will collapse rather suddenly

Assume that the column is retrofitted, with composite overwraps 80 percent hoops and 20 percent axials it will contain (confine) the damaged concrete causing it to act in triaxial compression. The composite laminate required can be sized by assuming a hydrostatic state with a pressure equal to the axial concrete stress which is 49.6 MPa (7200 psi). The hoop plies required are determined from:

$$\sigma = \frac{PR}{t} \Rightarrow t = \frac{PD}{2\sigma}$$

Plies made from E-Glass fibers/epoxy at about 50 percent fiber volume ratio have a tensile strength of about 1034 MPa (150 ksi) using a safety factor of 1.5. The corresponding allowable tensile stress is 689.5 MPa (100 ksi) using that value for σ and 30.5 cm (12 in.) for D we obtain:

$$t_{hoop} = \frac{49.6 \text{ MPa} \times (30.5/2) \text{ cm}}{689.5 \text{ MPa}} = 1.10 \text{ cm } (0.43 \text{ in.})$$

We therefore use 1.27 cm (0.5 in.) laminate with 1.0 cm (0.4 in.) hoops and 0.27 cm (0.1 in.) axials. This relatively thin laminate will prevent the column from collapsing.

This relatively straight forward illustrative example demonstrates the retrofit advantages by using composite laminate overwraps on axially loaded columns. In actual practice the column need to be retrofitted for loadings such as shear, torsion and local bending. Laminate configurations can be selected readily to accommodate those types of loadings. Of course with some thought reflection, other innovative ways to accommodate those loadings become evident. In the next two sections possible implications of more versatile retrofit concepts are illustrated.

COMPOSITE RETROFIT OF REINFORCED CONCRETE ARCHES

The special arch has a 20 m (65'-8") chord length and a 6m (20'-0") height (rise). The thickness of the arch 25.4 cm. (10 in.). The structural section is reinforced with two-way steel at the inner, outer and mid surfaces. The total volume ratio of the steel in the section is 0.67 percent. The arch is 26.0 cm (10'-3") wide at the base and 32 cm (1'-7") wide at the crown. A finite element model schematic of the arch and its structural sections are shown (Fig. 3). The arch is first evaluated without composite retrofits for two different load conditions: concentrated load at the crown and uniform pressure. Subsequently it is reevaluated with composite retrofits. The load carrying capacity of the reinforced concrete arch (without the composite retrofits) is determined incrementally by progressive fracture by using CODSTRAN [6]. The concentrated fracture load obtained by using CODSTRAN is 172.4 KN (38.8 Kips) while the collapse pressure is 0.019 MPa (2.8 psi). The CODSTRAN results for progressive fracture are shown (Fig 4).

Three curves are plotted as shown. Note the curves are normalized to the non-retrofitted arch. Enhancements from retrofits on either side (top or bottom) are substantial about two times from the top and three times from the bottom.

The conclusion, therefore, is that methods are available to size and locate infrastructure retrofits for substantial enhancements even though those methods were developed primarily for aerospace propulsion structures.

COM POSITE RETROFIT REINFORCED CONCRETE DOME

The concrete dome has 20 m (65'-8") chord and 6 m (20'-0") high (rise). A finite element model schematic of the dome is shown (Fig. 5). The structural section is identical to that for the special arch. (Fig. 6). The dome is first evaluated without the composite retrofit and then with it. The dome is subject4ed to concentrated load at the crown. The fracture load is determined by cumulative progressive structural fracture by using CODSTRAN [6]. The concentrated fracture load for the dome obtained by using CODSTRAN is 310 KN (69.72 Kips). Normalized values of the damage accumulated are plotted versus normalized force in Figure 6 for three different conditions: Without retrofit, bottom retrofit and top retrofit. As can be seen, the enhancement with the top retrofit (reinforcement) are about five times, compared to that without retrofit. The enhancement for the bottom retrofit is only marginal and perhaps it may not be even cost effective.

The conclusions from the retrofitted dome are: (1) retrofitting must be properly designed and placed to obtain the desired and even additional load carrying capacity, and (2), structural fracture and respective loads can be realistically determined by progressive fracture, and (3), methods developed for aerospace propulsion structures are readily adaptable to composite retrofit designs.

CONCLUSIONS:

The important conclusions from an investigation to design composite retrofits for reinforced concrete infrastructures are as follows:

1. Composite mechanics and progressive structural fracture methods are available to select and place retrofit laminates for substantial design load enhancements.

2 Axially loaded columns can be enhanced to twice their design load by relatively thin laminate hoop wraps [1.0 cm (0.4 in.)].

3. Arch-type reinforced concrete infrastructure subjected to concentrated load are most enhanced by bottom retrofitting laminates.

4. Dome-type reinforced infrastructures subjected to concentrated load at the apex are most enhanced by top retrofitting laminates.

5. Computational composite and structural mechanics methods developed for aerospace structures are readily adaptable to retrofitting of reinforced concrete infrastructures.

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TECHNICAL BIOGRAPHIES
DR. C. C. CHAMIS

Dr. Chamis is a Senior Aerospace Scientist in the Research and Technology Directorate at NASA Lewis Research Center. His major research has focused on the development of computational simulation methods for composite mechanics, probabilistic structural analysis and probabilistic composite mechanics. His current research is the development of computational simulation methods for coupled multi-discipline problems, technology benefits estimators and for concurrent engineering. In addition, he is continuously conducting research to identify benefits of technology transfer to non-aerospace applications. A good example of this is the present article. Dr. Chamis is a frequent contributor to SAMPE Technical Meetings and is a SAMPE Fellow.

DR. P. K. GOTSIS

Dr. Gotsis is a Research Engineer in the Structures and Acoustic Division at NASA Lewis Research Center. Is major research has focused on the development of computational simulation methods for composite mechanics, structural analysis, structural optimization and damage progression on fiber composite structures.

Key Words:

Composite mechanics, finite element, progressive fracture, columns, arches, domes, fiber composites, fracture load, reinforced concrete.

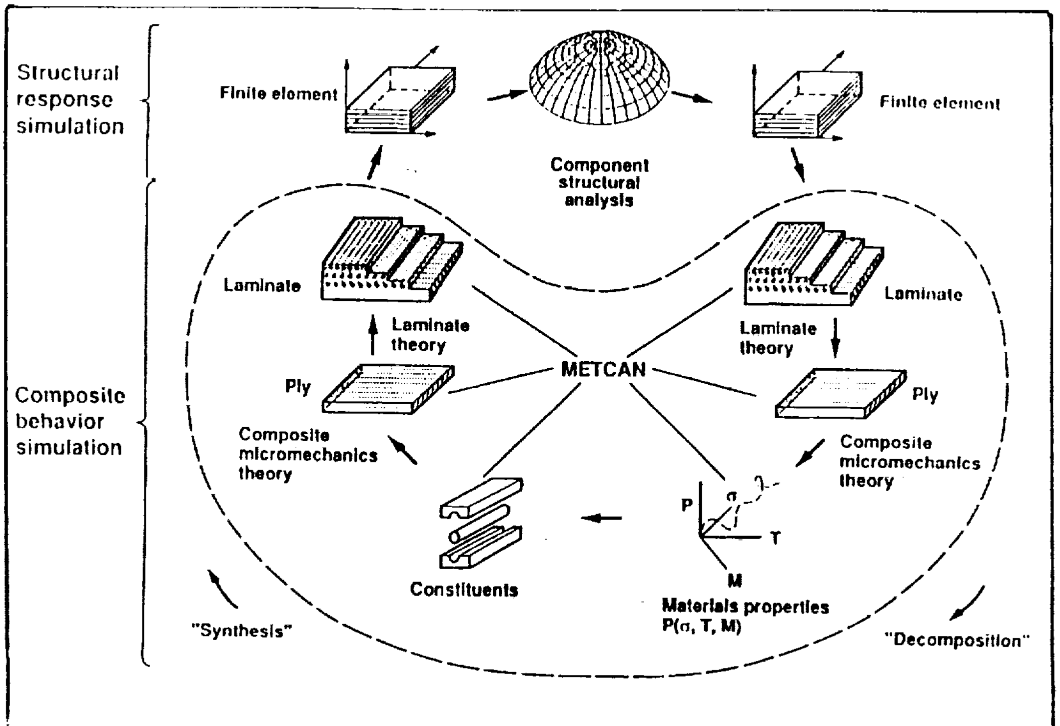

Figure 1 - Computational simulation cycle for composite structural analysis.

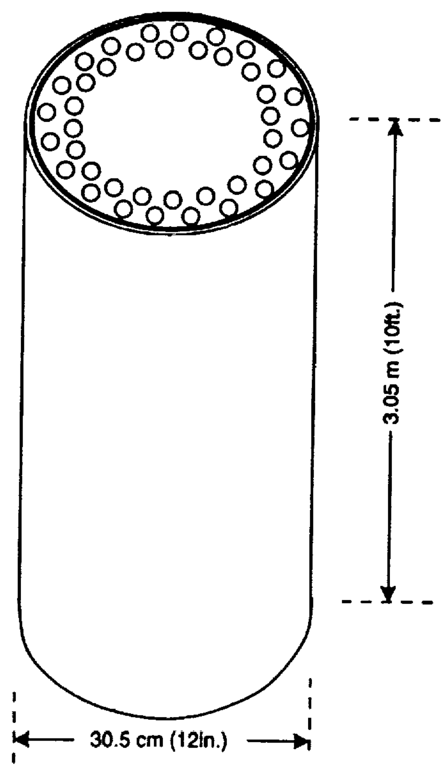

Figure 2 - Reinforced concrete column schematic
(Assumed reinforcing steel area three percent)

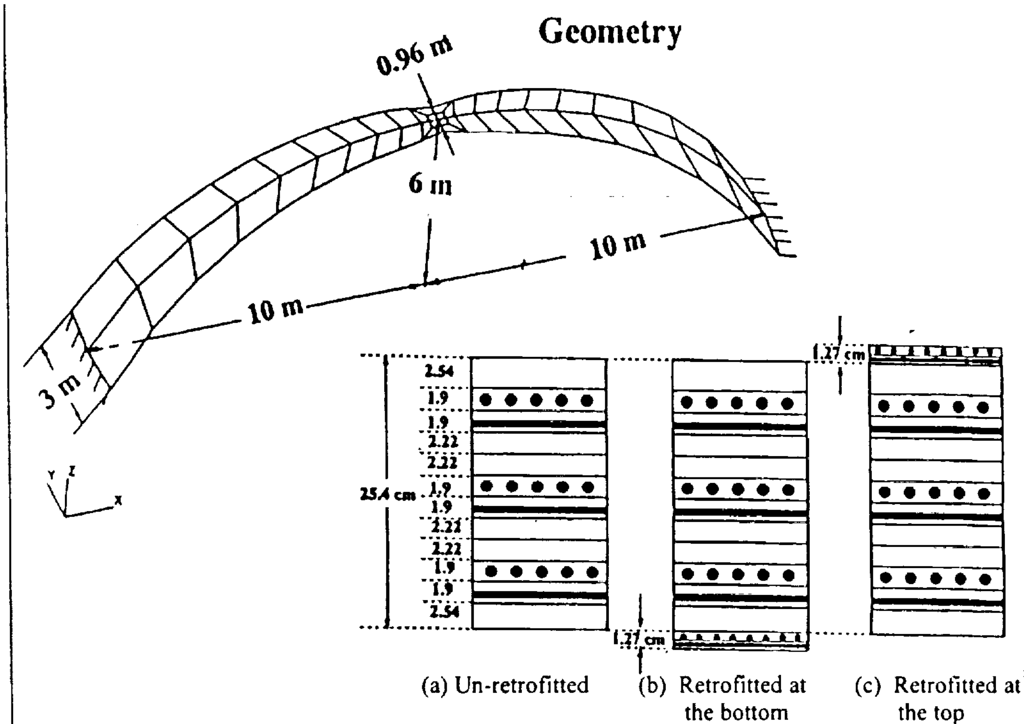

Figure 3 - Specialty arch geometry and structural sections.

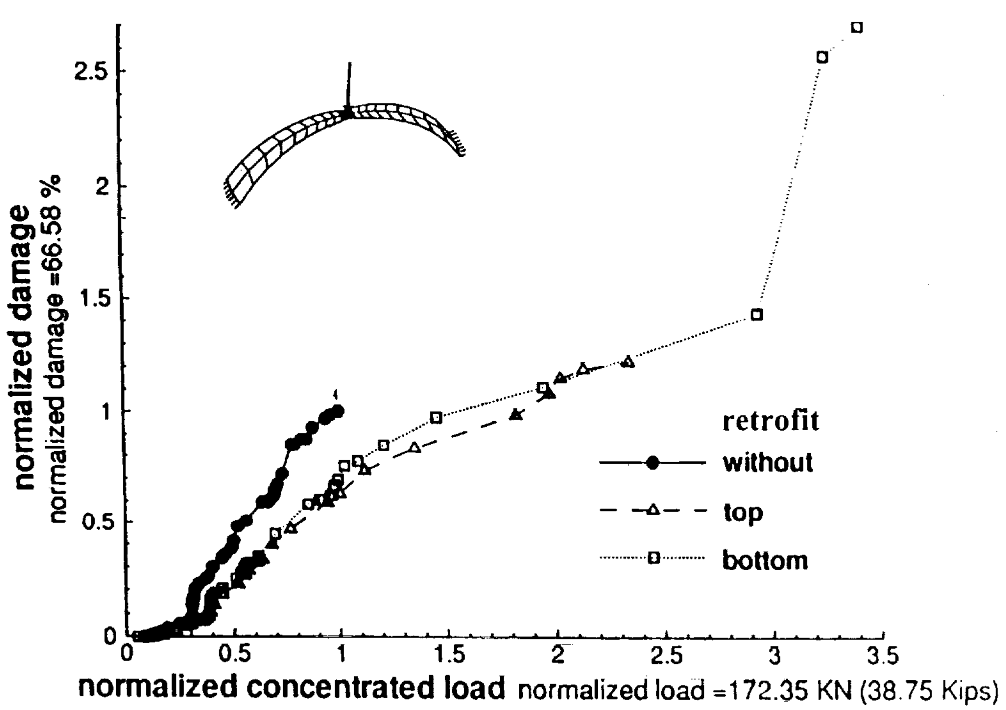

Figure 4 - Specialty concrete reinforced arch: Benefits of composite retrofit [E-Glass-fiber/polymer; 0.55 fiber volume ratio; 1.27 cm (0.5 in.) thick layer].

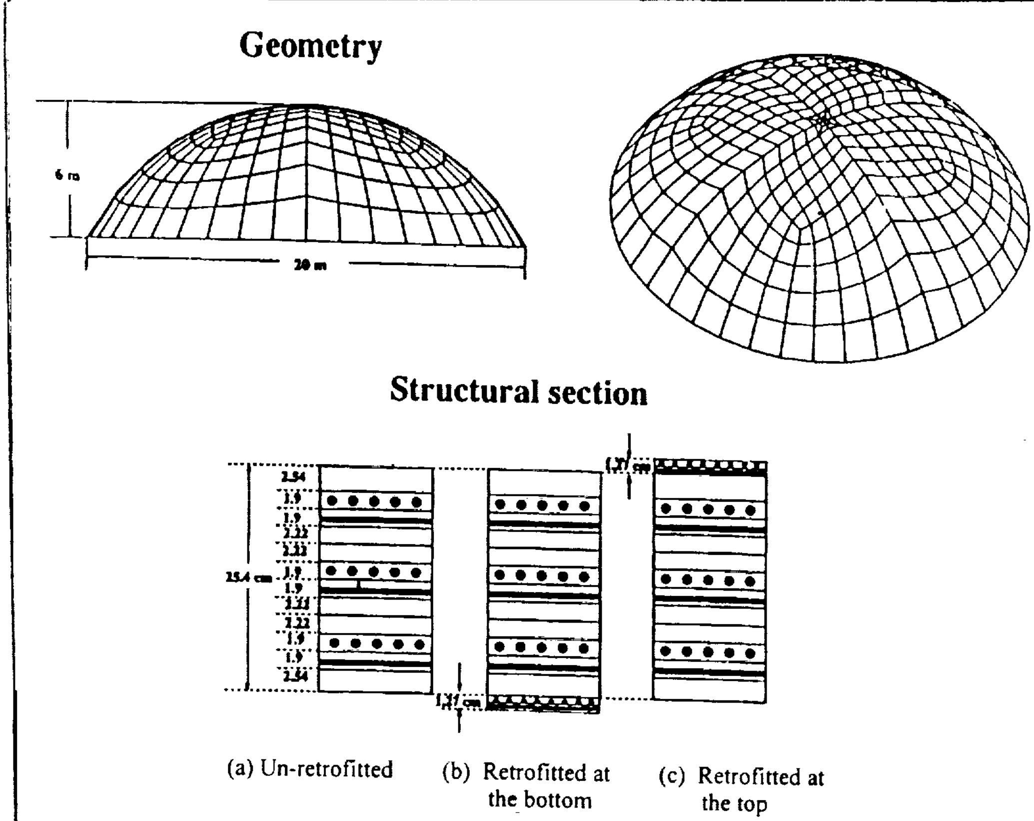

Figure 5 - Reinforced concrete dome geometry and structural sections.

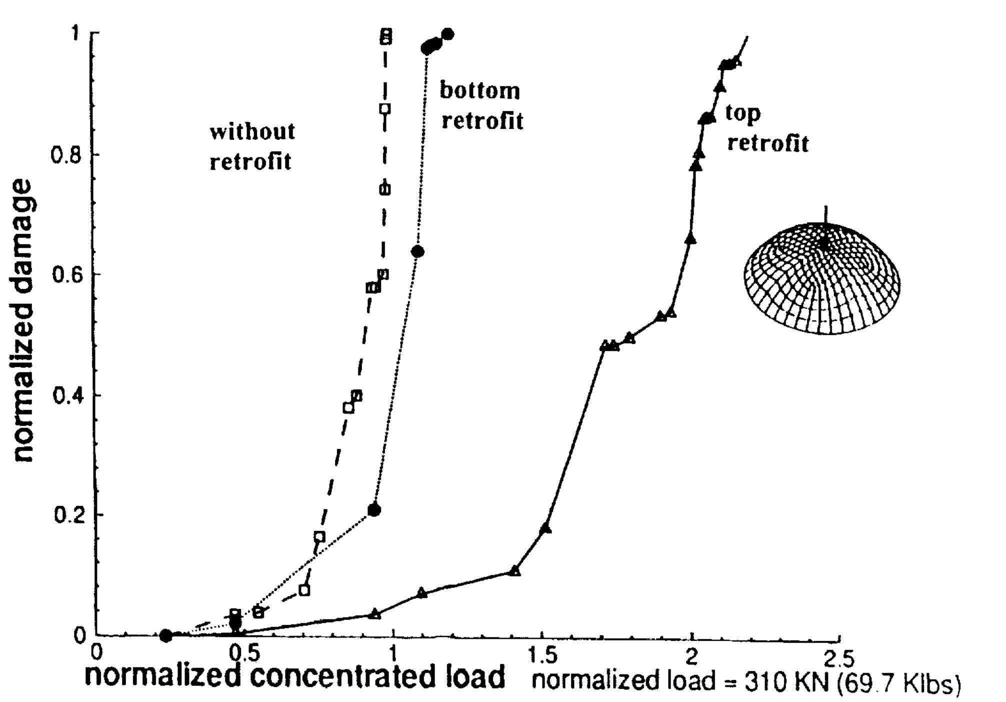

Figure 6 - Retrofitted concrete dome: Benefits of composite retrofit [E-Glass-fiber/polymer; 0.55 fiber volume ratio; 1.27 cm (0.5 in.) layer thickness].